

# Integrating Large-Scale Variable Renewable Energy Resources on the Transmission Grid: A Case Study of the Nigerian Transmission System



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**ABSTRACT:** A more sustainable energy mix is the purpose of the global energy transition, which aims to minimize the energy sector's dependence on fossil fuels. To provide sustainable and reliable energy generation and to evaluate grid stability, it is critical to estimate the level of renewable energy penetration in power grids. In this work, an overview of solar and wind energy potential in Nigeria was assessed. The Nigerian transmission power system was simulated using DIGSILENT PowerFactory software. There were 48 buses in the modelled 330 kV network, which was simulated under normal operating conditions for a simulation time of 15 seconds. The simulation considered four scenarios: the base case, 10%, 20%, and 30% wind and solar penetration. The effect of increasing the variable renewable energy sources was observed in the voltage profile as well as the frequency of the grid. Frequency was lowest in the scenario with 30% variable renewable integration, which was not within the normal operating range, this was due to higher portion of variable renewable energy in the network. The voltage profile of 10% and 20% renewable penetration levels showed some buses that exceeded the set limits which would cause voltage instability in the system. Results highlight the importance of ensuring voltage and frequency stability across the system, especially as the renewable energy penetration increases. Also, results suggest the need for additional control strategies, to guarantee stability in the power system.

**KEYWORDS:** Energy Transition, Renewable Energy Integration, Solar, Variable Renewable Energy, Wind

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## I. INTRODUCTION

Achieving a sustainable energy mix involves increasing the share of renewable energy while decreasing the need for fossil fuels. However, the targets established to drive this transition remain unmet, posing serious risks to natural ecosystems, human societies, and global economies. Failure to meet these goals jeopardizes the ability to limit global warming to 1.5°C, with potentially devastating consequences (IRENA, 2023a). The decarbonization of various industries and widespread electrification has made the power sector the backbone of the integrated energy system, meeting the majority of primary energy demand (Ludereret et al., 2019; Jain et al., 2023; Véliz et al., 2025). Also, this will lead to the power relying more on variable renewable energy sources, primarily wind and solar (Bogdanov et al., 2021). The global energy transition aims to reduce the energy sector's reliance on fossil fuels, which currently dominate energy production and consumption, by shifting toward a more sustainable energy mix. The renewable energy share of electricity capacity of some selected countries

including Nigeria, Kenya, South Africa, China, Germany, USA, and Australia as obtained from (IRENA, 2023b) is presented in Figure.1 It can be observed that for most countries the share of renewable energy in the electricity capacity has had a gradual increase from the year 2013 to 2022.

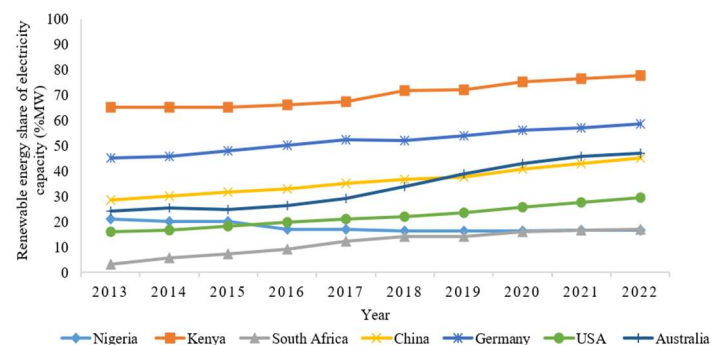


Figure 1. Yearly renewable energy share of electricity capacity of various countries (IRENA, 2023b)

Figure 1 Yearly renewable energy share of electricity capacity of various countries (IRENA, 2023b)

The integration of variable renewable energy sources with high shares into the power grid is a critical problem for  
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decarbonization and clean energy plans on a global scale (Medina et al., 2022; Davis et al., 2023). In many nations, large-scale renewable energy is anticipated to be added to the existing grid and the renewable energy sources with the most potential that provide significant amounts of electricity are solar and wind energy. Location dependency, non-controllable fluctuation, and partial unpredictability are some of the features of generating power via variable renewable energy sources such as solar and wind energy (Li et al., 2021; Zheng et al., 2023). These features of the variable renewable energy sources can affect the grid's security and functionality when integration is taken into account (Alshahrani et al., 2019). Some studies have considered the effect of increasing the penetration level of variable renewable energy sources into national grids. Medina et al. (2022) proposed transmission as a key factor in fostering such high penetration, stating that transmission was the subject of renewed interest in the energy sector and strengthening and expanding the transmission network was the best technical solution to reach high penetration levels of variable renewable energy sources.

Evaluating the renewable energy penetration level in power grids is important in ensuring sustainable and reliable energy generation and assessing grid stability. In this paper, the effects of integrating large-scale wind and solar into the Nigerian national grid were studied. This is critical for planning future grid expansions, upgrading grid infrastructure, and ultimately achieving a more sustainable and resilient power system. Nigeria is the biggest economy in sub-Saharan Africa, but its ability to grow is constrained by the lack of access to power. Nigeria has a wealth of energy resources, including hydro, solar, wind, oil, and gas. Currently, the installed capacity of the Nigerian power grid is about 13GW of electricity (Adoghe et al., 2023). However, it can only deploy 4 GW – 5 GW of power on the majority of days, which is not sufficient for a country with more than 233 million people (World Population Prospects - Population Division - United Nations, 2024). The fundamental motor of global industrialization, technological development, engineering revolution, and economic expansion is electricity. Recent research reveals that the government of Nigeria is lagging in implementing renewable energy technology, a purposeful shift away from non-renewable sources of electricity energy toward renewable and ecologically friendly sources is essential for national growth (Akuru et al., 2017; Obada et al., 2024).

Despite the unbundling of the Nigerian power sector, policies, generation, and transmission master plans, renewable energy goals, and alliance with the West African Power Pool (WAPP), there exist challenges with all components of the grid in Nigeria (Ezekwem & Muthusamy, 2023). Some of these issues as reported in previous literature are stated as follows: generation is dependent on gas with inadequate supply, old generating stations, and equipment, transmission has low electricity wheeling capacity, poor voltage stability, and vandalization of the lines and equipment, weak distribution and insufficient network coverage, poor billing system, electricity theft, and insufficient funds for maintenance activities. At the consumer's end, some are unable to pay for the services they receive, and with the population increase, energy access remains a problem for some rural communities.

The information infrastructure lacks the required up-to-date technologies for communication and monitoring of the grid. For now, there is no storage asset in the Nigerian power grid. There is a lack of clear policies on how to achieve renewable penetration in the electricity generating sector (Akuru et al., 2017; Ogunmodimu & Okoroigwe, 2019; Somoye, 2023). There is therefore a need to improve the electricity generation by exploring other sources other than gas and maintaining both the voltage and frequency stability of the Nigerian power grid.

## II. RENEWABLE ENERGY POTENTIAL IN NIGERIA

Nigeria has abundant natural renewable energy resources that are crucial to the nation's sustainable growth, but they are currently underutilized. These renewable energy sources include wind, hydro, solar and biomass (IRENA, 2023c).

### A. Solar Energy Potential in Nigeria

Solar energy involves harnessing sunlight to produce energy. Sunlight is the primary energy source for the Earth's surface, and most forms of energy we use originate from the sun which includes oil, coal, natural gas, wood, and wind (Kalogirou, 2023; Pourasl et al., 2023). In Ogunmodimu & Okoroigwe (2018), concentrating solar power technologies including parabolic trough concentrators, parabolic dish concentrators, and solar towers, were analyzed under operational, environmental, and social conditions in Nigeria to determine the most suitable technology for solar thermal electric power plants. Given its proven technology maturity and flexible financing mechanism, Ogunmodimu & Okoroigwe (2018) considered the trough system to be the most appropriate for immediate and medium-term projects. Okoye et al. (2016) conducted a preliminary analysis on the potential use of solar-based technologies for electricity generation in three strategically selected Nigerian cities: Onitsha, Kano, and Lagos. As shown in Figure 2, solar energy is available in Nigeria for electricity production.

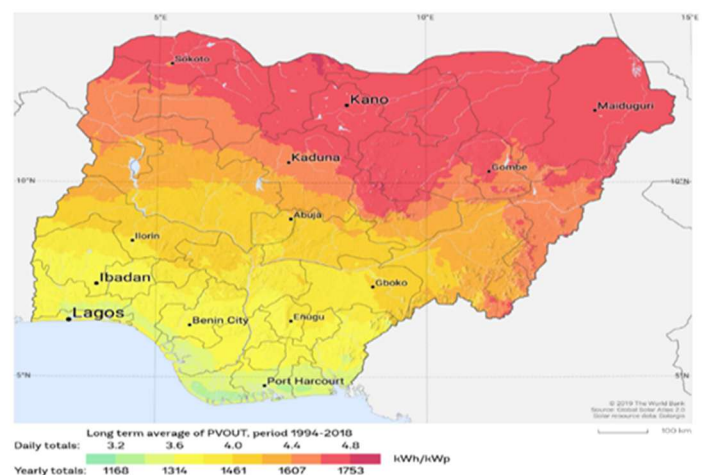


Figure 2 Solar PV potential of Nigeria (Atlas, 2022)

### B. Wind Energy Potential in Nigeria

Wind energy has one of the quickest growth rates in the global renewable energy market due to its inherent qualities of being

clean, abundant, economical, and ecologically beneficial (Summerfield-Ryan & Park, 2023; Hassan et al., 2024). Wind turbines and windmills that produce electricity, as well as wind and water-abstraction pumps, are examples of common wind power equipment. In Nigeria, numerous studies on wind energy potential and wind speed analysis have been conducted. Unlike solar energy which is mainly used in rural communities and government higher institutions of learning in Nigeria for electrification projects, wind has been given inadequate attention, with only one wind farm of 10 MW rating in Katsina state (Idris et al., 2020). Figure 3 shows a map of the wind potential in Nigeria.

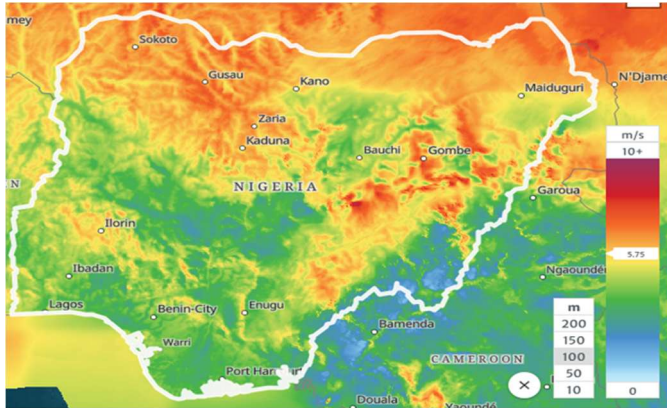


Figure 3 Wind potential in Nigeria (Davis et al., 2023)

### III. ROLE OF POLICY IN RENEWABLE ENERGY INTEGRATION

Utilizing renewable energy has become more significant as a means of addressing environmental problems and the energy crisis. Strategies, regulations, and policies that can lower greenhouse gas emissions and increase energy efficiency are necessary for sustainable development (Li et al., 2022). According to IRENA's 1.5°C scenario, the proportion of renewable energy in the world's energy mix would rise from 16% in 2020 to 77% by 2050. Under the 1.5°C scenario, electricity is projected to become the dominant energy carrier by 2050, accounting for over half of total final energy consumption (IRENA, 2023c). According to a study by Shem et al. (2019), findings show that regulations need to include mechanisms that favour renewable energy technologies and also encourage the mobilization of private investment or international cooperation to support the shift towards low carbon emissions. Additionally, there is a close correlation between the advancement of the clean energy sector and the achievement of pertinent Sustainable Development Goals. A correlation like this should make actions related to the energy sector results-oriented. In Chang et al. (2021), it was stated that tools for modelling energy systems must be clear and applicable to be put to good use. It should not be difficult to understand the assumptions and findings due to the intricacy of these technologies. The goal of model creation should be to produce insightful research that can successfully support policies and direct decision-making.

Developed strategies to increase the ratio of renewable energy in Nigeria often focus on hydro power plants. Wind and solar energy are also taken into account, though not primarily for

large-scale grid integration. Energy production with hydropower has increased over the years, but there is little emphasis on using large-scale solar and wind for the power grid. Research-based policies and regulations are therefore required to enable the increased share of both solar and wind energy to utilize these abundant resources and improve electricity access. Several plans and policies govern electricity generation in Nigeria, some of which are discussed here.

#### A. Renewable Energy Master Plan (REMP)

This Master Plan was developed to increase Nigeria's renewable electricity share from 13% in 2015 to 23% by 2025 and 36% by 2030. In 2015, hydropower was the primary source of renewable energy, but the projected increases in 2025 and 2030 relied on diversifying the national electricity mix. The plan set ambitious capacity targets for solar thermal, wind, biomass, and solar photovoltaic technologies. By 2025, small hydropower was expected to grow from 600 MW in 2015 to 2,000 MW, solar photovoltaics to reach 500 MW, and biomass to expand from 50 MW to 400 MW. Wind energy capacity was also targeted to achieve 400 MW by 2025. Meeting these targets would aid renewable energy to account for 10% of Nigeria's total energy consumption by 2025. In addition to boosting power generation, the REMP aimed to enhance energy access nationwide, targeting growth in electricity availability from 42% in 2005 to 60% in 2015 and 75% by 2025, focusing on both urban and rural areas. To achieve these goals, the REMP emphasized the need to establish a dedicated institutional framework, including a specialized fund and agency, to support the deployment and integration of renewable energy (NERC, 2023).

#### B. National Renewable Energy and Energy Efficiency Policy

This framework intends to enhance access to energy services while ensuring the sustainable growth of eco-friendly energy's share in Nigeria's energy mix. The National Renewable Energy and Energy Efficiency Policy outlines Nigeria's commitment to renewable energy and energy efficiency, providing a clear roadmap for the sustainable development, deployment, and application of renewable energy resources. It addresses both grid-connected and off-grid solutions, as well as urban and rural renewable energy technologies. It also mandates important regulations and rule modifications and develops an energy efficiency strategy. The strategy represents the first steps toward bringing Nigeria's renewable energy and energy efficiency policies in line with those of the Economic Community of West African States (Nebo & Wakil, 2015).

### IV. MATERIALS AND METHOD

The Digital Simulation of Electrical Networks (DIgSILENT) PowerFactory software was used to simulate and analyze the steady-state and transient voltage and frequency stability of the Nigerian transmission power systems under normal operating conditions. The time step used for the frequency simulation was 0.01 seconds with a simulation period of 15 seconds. Nigeria's transmission system includes 132 kV and 330 kV

lines and substations. The thermal power plants are in the south of the country at Egbin, Alaoji, Afam, Delta, and Olorunsogo, close to gas reserves, while the hydropower plants are in the north, at Jebba, Kainji, and Shiroro. The distribution network is divided into 11 zones and consists of 11 kV, 33 kV, and low voltage circuits. The nominal frequency of the Nigerian power system is 50 Hz (The Nigeria Electricity System Operator, 2023).

There are ongoing plans for renewable energy generation such as new hydropower plants and photovoltaic and wind

power plants to be introduced into the Nigerian power grid to help improve its current lack of generation capacity. Non-renewable generation such as large coal-fired power stations may be required in the future to generate sufficient baseload power (Transmission Company of Nigeria, 2018). For this work, the non-renewable generators were sized down while the hydropower plants were kept constant. This was done to favour the overall share of renewable energy. The generation capacity for the various scenarios is presented in Table 1.

Table 1 Generation capacity of the scenarios

Energy source	Unit	Base case	10% Solar and Wind Generation	20% Solar and Wind Generation	30% Solar and Wind Generation
Solar	MW	0	200	400	600
Wind	MW	0	264	524	792
Hydro	MW	1,016.19	1,016.19	1,016.19	1,016.19
Other power plants	MW	3,744.23	3126.47	2,661.21	1,652.237

The single line diagram of the modelled and simulated Nigerian 330 kV Transmission network with large scale solar and wind placement is shown in Figure 4. The modelled network consists of 48 buses and 13 generators.

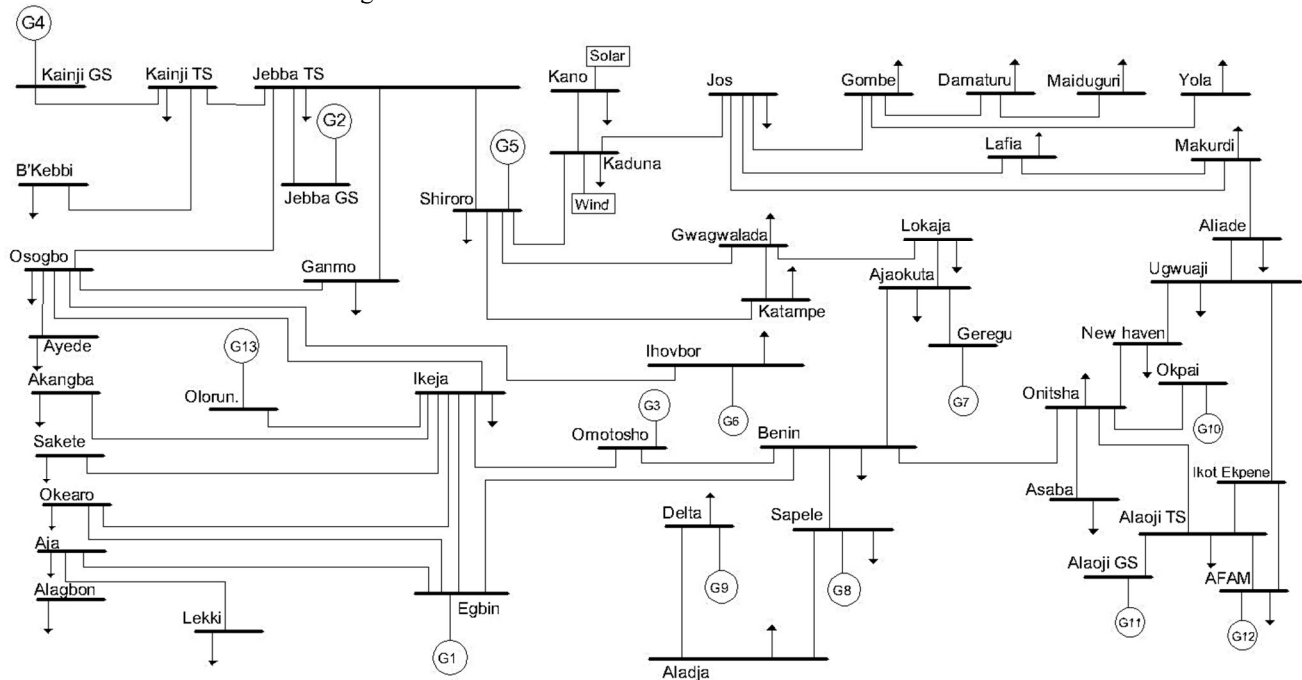


Figure 4. Single-line diagram of the simulated Nigerian transmission power system

A. Load Allocation

Load allocation in power systems is done to distribute the total power demand among different substations, zones, or distribution companies. To prevent overloading or disruptions in the system's ability to supply power, load allocation aims to keep each generator operating within its capabilities. This is done by calculating the optimal distribution of load based on factors such as generator capacity, transmission constraints,

and overall demand. In the Nigerian electricity system load allocation has been done by the Nigerian Electricity Regulatory Commission (NERC) and according to different distribution companies. The load allocation to the distribution companies by NERC is presented in Figure 5.

V. RESULTS AND DISCUSSION

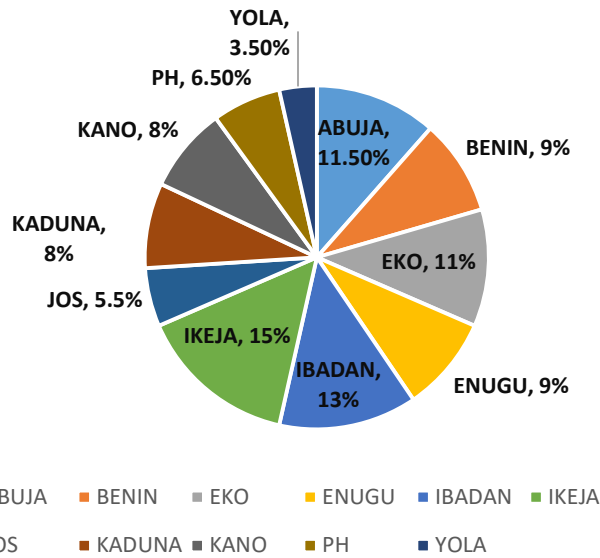


Figure 5. Load allocation to the DISCOs by NERC's MYTO (National Bureau of Statistics, Nigeria, 2023)

The operational report of the Nigerian power grid for three days (26th of April 2023, 8th of October 2022, and 11th of February 2022) is presented in Table 2. From Table 2 it can be deduced that the lowest voltage recorded (299 kV which is equal to 0.9061 pu) is below the operational limits and the highest voltage recorded (360 kV which is equal to 1.0909 pu) is way above the operational limits specified by NERC (The Nigeria Electricity System Operator, 2023). It can also be deduced from Table 2 that the highest and lowest system frequencies are not within the range for normal operation. However, NERC permits frequency limits of 50 Hz +/- 2.5% (48.75 – 51.25 Hz) for a brief time when the system is under stress. The highest system frequency (51.142 Hz) is within the range for a system under stress and the lowest system frequency (48.36Hz) is within the extreme system fault conditions range as specified by NERC. This indicates that system sometimes operates under stress and extreme system fault conditions.

Table 2. Operation report of the Nigerian power grid

	Units	26-04-2023	08-10-2022	11-02-2022
Peak Generation	MW	4205.9	4263.7	4761.4
Lowest Generation	MW	3694.7	3722.1	4080.7
Energy Generated	MWH	94505.59	97661.74	106809.07
Energy Sent Out	MWH	93202.28	96304.3	105054.97
Highest System Frequency	Hz	51.142	50.76	50.729
Lowest System Frequency	Hz	48.84	49	48.36
Highest Voltage Recorded	kV	354	347	360
Lowest Voltage Recorded	kV	300	299	300

The renewable resources are not evenly distributed as shown in Figure 1 and Figure 2, Birnin Kebbi, Kaduna, Kano, Jos, Maiduguri, Damaturu, Gombe, and Yola 330 kV stations are located where there are highest solar irradiances for the production of electricity. Kaduna, kano, Damaturu, Jos, and Laffia 330 kV station locations have the best wind speeds in the Nigerian 330 kV grid for generating electricity. Selection of site was done because among these stations Kaduna and Kano had the highest load allocations. For the placement, a large-scale wind power plant in Kaduna was chosen. For the placement of a large-scale solar power plant, Kano was selected. The reason was to place generation close to the load.

Figure 6 shows the variation of steady-state voltages in per-unit across different buses in the Nigerian 330 kV power system under different scenarios of renewable energy integration. Some buses at 10% and 20% renewable penetration levels exceeded the limits, indicating potential instability. It was observed that there were changes in the voltage profile for different scenarios, this is illustrated in

Figure 6. However, the scenario with 30% variable renewable integration had the best voltage profile.

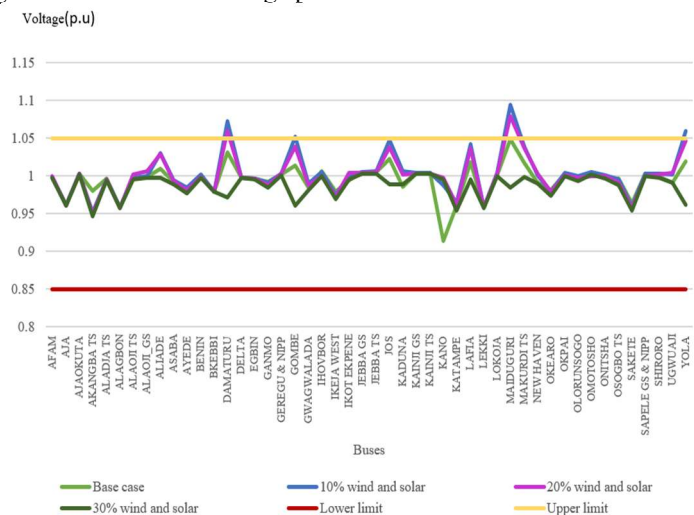


Figure 6 Comparison of the steady state voltages of different scenarios

The frequency response of the grid for 15 seconds is shown in Figure 7. It can be observed that there is an initial frequency

dip for all three scenarios involving renewable energy penetration. The frequency dip is more significant as the solar

and wind penetration increases. At 10% penetration, the system is more robust and recovers quickly to a stable frequency of 49.87 Hz. The grid's frequency at 20% penetration has a slightly slower recovery and stabilizes at a 49.74 Hz. When compared to the 10% and 20% scenarios, the 30% penetration has a significant drop and the slowest recovery. This suggests a reduction in system inertia due to the higher integration of renewables since wind and solar systems typically lack the rotational inertia of conventional synchronous generators.

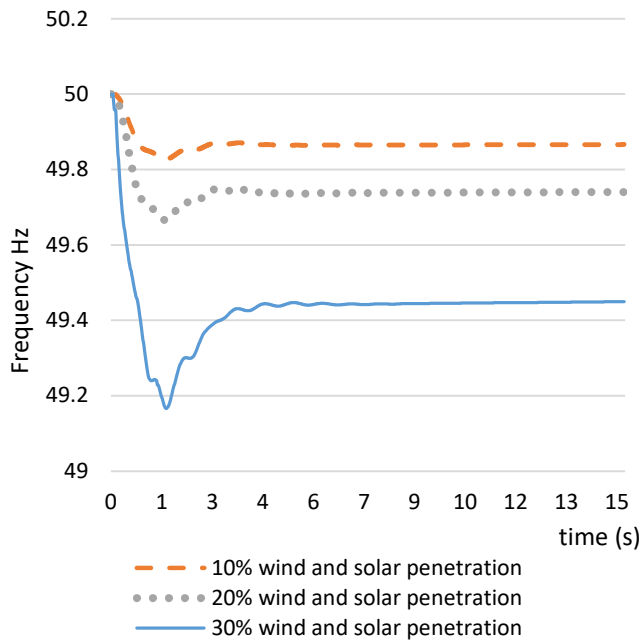


Figure 6 Frequency vs time graph for various solar and wind penetration levels

From Figure 8, the frequency of the scenario with 30% variable renewable integration had the lowest frequency which was not within the normal operational limits set by the regulation agency in Nigeria. Due to the substantial technical, social, and economic effects of grid instability and unreliability, it is imperative to develop solutions that stabilize the grid and ensure a dependable service. According to Medina et al., (2022), integrating high levels of variable renewable energy source introduces a fresh approach to how power networks are set up and run, presenting new issues and difficulties related to stability and reliability. This is due to the intermittent nature of variable renewable technologies (Alshahrani et al., 2019). Already the Nigerian power grid has an increased mismatch between the demand and supply of power which raises concerns about the ability of the nation to meet its vital energy security and sustainability targets in a demography-growing environment (Magazzino et al., 2023). Integrating high levels of wind and solar as shown in this study would affect the stability of the grid.

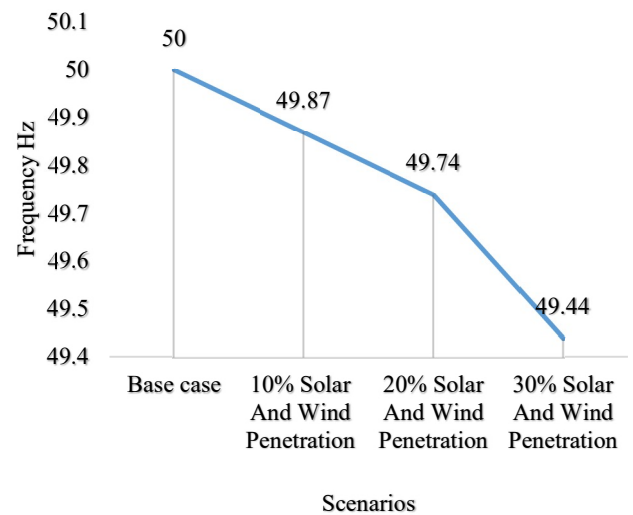


Figure 7 Frequency of different solar and wind penetration levels

## VI. CONCLUSION

One of the largest issues facing the world's society is the shift to long-term sustainable energy systems. Since solar and wind are in abundance in the demography, research on solar and wind energy integration into the Nigerian grid to improve power generation while taking into account stability issues associated with variable energy sources was conducted. Effective policies are useful in the adaptation of sustainable energy technology and the integration of renewable energy. There are policies in Nigeria to increase the country's share of renewable energy in the power sector. However, hydropower plants are the only source of renewable energy currently connected to the national grid. Integrating large-scale wind and solar can be useful in enabling the nation to reach its 36% Renewable Energy Master Plan goal by 2030. However, integrating this high level of variable renewable energy would make the grid unstable and extra measures will be needed to stabilize the power grid. As wind and solar integration increased from 10% to 30%, the voltage levels at some buses varied more significantly, which indicates the challenges of integrating renewables without proper voltage control mechanisms. Higher renewable energy penetration reduces system inertia, making the system more susceptible to frequency deviations. There is therefore a need for additional measures, control technologies, and technologies to improve the grid's stability and aid the adoption of variable renewable sources in the power grid.

**J. A. Onwuzuruike:** Conceptualization, Software, Validation, Manuscript preparation, Writing. **S. U. Hussein, B. B. Adetokun, and O. Oghorada:** Supervision.

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